



Development of a low-flow hazard model for the Fraser basin, British Columbia

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Mountain Pine Beetle working paper 2009-14

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Abstract

The province of British Columbia, Canada, is currently experiencing the largest mountain pine beetle outbreak ever recorded in North America. The most recent surveys indicate that widespread mortality of pine trees has occurred in over 10 million ha of forest (an area roughly the size of Iceland) and the outbreak continues to kill mature pine in the province. The epicentre of the current outbreak is in the Fraser River drainage basin ($230,000 \text{ km}^2$), where roughly 8 million ha of forest have been affected, approximately 35% of the drainage area. Due to the infestation's area and associated salvage harvest operations, the potential exists for widespread and significant local and regional hydrologic impacts within the basin. However, the scale and physiographic heterogeneity of the Fraser River basin precludes both direct observation and extrapolation of hydrologic impacts observed from a limited number of stand-level and small-basin experiments.

A low-flow hazard model was developed for third-order catchments within the Fraser River watershed. Baseline and mountain pine beetle-infestation and harvest scenarios were modeled for seven catchments for direct comparison with the Variable Infiltration Capacity modeling results. The model is to be used in risk-based hydrology modeling to produce a comprehensive knowledge of mountain pine beetle-infestation effects on the hydrology of the Fraser River watershed and its major sub-basins in British Columbia, Canada.

Keywords: Hydrology, risk-based modeling, hydrological modeling, peak flow, low flow, scenarios

Résumé

La province de la Colombie-Britannique, au Canada, connaît actuellement la plus forte infestation par le dendroctone du pin ponderosa jamais enregistrée en Amérique du Nord. Les derniers sondages indiquent que la mortalité des pins s'est étendue sur plus de 10 millions d'hectares de forêt (une zone correspondant plus ou moins à la taille de l'Islande), et l'épidémie continue de ravager des pins matures dans la province. L'épicentre de l'infestation actuelle se trouve dans le bassin de drainage du fleuve Fraser ($230\,000 \text{ km}^2$), où près de 8 millions d'hectares de forêt ont été touchés, soit environ 35 % de l'aire de drainage. Étant donné la zone d'infestation et les opérations de coupe de récupération qui y sont associées, il y a des risques de répercussions hydrologiques générales et considérables à l'échelle locale et régionale à l'intérieur du bassin. Cependant, l'échelle et l'hétérogénéité physiographique du fleuve Fraser excluent à la fois l'observation directe et l'extrapolation des répercussions hydrologiques observées à partir d'un nombre limité d'expériences sur le terrain et sur de petits bassins.

Un modèle de faible débit a été élaboré pour les captages d'eau de troisième ordre à l'intérieur du bassin versant du fleuve Fraser. Les scénarios de référence, d'infestation par le dendroctone du pin et de coupe ont été établis pour sept captages d'eau, pour permettre une comparaison directe avec les résultats du modèle à capacité d'infiltration variable. Ce modèle a été développé lors de la modélisation hydrologique fondée sur le risque pour acquérir des connaissances approfondies sur les effets de l'infestation par le dendroctone du pin ponderosa sur l'hydrologie du bassin versant du fleuve Fraser et de ses principaux bassins secondaires en Colombie-Britannique, au Canada.

Mots clés : hydrologie, modélisation fondée sur le risque, modélisation hydrologique, débit de pointe, faible débit, scénarios

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1 Introduction

Low flow is the lesser studied of the two hydrological extremes. Low flow is not a sudden phenomenon; rather, it takes a long time to develop. However, due to its persistence, socio-economic and environmental impacts can be similarly significant to those of floods (Smakhtin 2001). In a summary of a recent workshop and a special issue of the *Canadian Water Resources Journal*, Whitfield (2008) provides a list of conclusions that include the need for groundwork which, since existing models fail to predict low flows accurately, includes the development of new methods and models for prediction of low flows in ungauged catchments, and the prediction of changes due to land-use and climate changes.

This chapter gives an overview of what is known about low flows in British Columbia and the hydrologic hazard related to low flows. It provides the background information needed to design the hazard model and provides the hydrologic rationale for the model. It also summarizes low-flow estimation and regulation progress in other jurisdictions.

1.1 Factors influencing low flows

1.1.1 Climate

Input to the surface and subsurface hydrologic system comes from either rainfall or snowmelt. A lack of input into the hydrologic system over an extended period of time will lead to the recession of the streamflow hydrograph and ultimately to *low flow*. Low flows, then, can result from two meteorological situations:

- an extended dry-weather period with a climatic water deficit, or
- cold temperatures that cause storage of precipitation as snow.

Across British Columbia, one or both of these situations regularly persist during different times of the year. The resulting low flows are commonly distinguished by referring to them as *summer low flow* or *winter low flow*. A recent review of low-flow processes, patterns and impacts in Canada can be found in Burn et al. (2008).

Climate determines the magnitude and variation of temperature, precipitation, and potential evapotranspiration over the year. Monthly climate normals hence provide a valuable source of information for a first assessment of the climatic drivers and the expected timing of low flows in a particular region. However, climate varies spatially, especially in mountain regions. Climate also varies temporally at interannual, decadal and longer time scales and this variation can change. Long-term trends and changes in the climate system induce changes to low-flow characteristics.

1.1.2 Catchment storage

While climatic drivers lead to a water surplus in one season and a water deficit in another season, catchment controls determine how any such surpluses and deficits propagate through the system and into streamflow. During a deficit period, soil moisture is depleted through soil evaporation and water uptake by vegetation (transpiration). Other storages are depleted through outflow, depending on factors such as the storage level and hydraulic resistances (e.g. connection to the stream). Both recession behaviour to low flow and low-flow magnitude therefore depend on the characteristics of the various storage opportunities in the watershed. Prediction of low flows hence requires continuous monitoring and/or modeling of catchment storage status (e.g. groundwater and lake levels, soil moisture) not only during the deficit period but also as they are being recharged during the previous surplus period.

Important human influences on low flows include not only the abstraction of water from catchment stores such as lakes, groundwater, and streamflow, but also the discharge of effluents

into the channel and low-flow augmentation due to regulated outflow from reservoirs. Abstractions and effluent discharges are direct impacts. Human influences can also indirectly affect low flows by altering catchment processes, e.g., land-use changes such as deforestation, afforestation, urbanization, and induced deglaciation from global climate change.

1.1.3 Low-flow regimes in British Columbia

Hydrological regimes in the Canadian Cordillera are predominantly nival with winter low flows (Figure 1). Exceptions are low elevation pluvial regimes along the coast, where summer is the primary low-flow season (Figure 1 – Carnation Creek). The beginning and end of the winter low-flow season in the nival rivers depends on when temperatures drop below or rise above freezing. As winter temperatures generally decrease with elevation, with distance from the coast, and with latitude, the timing of winter low flows is controlled by the location and elevation of a given basin.

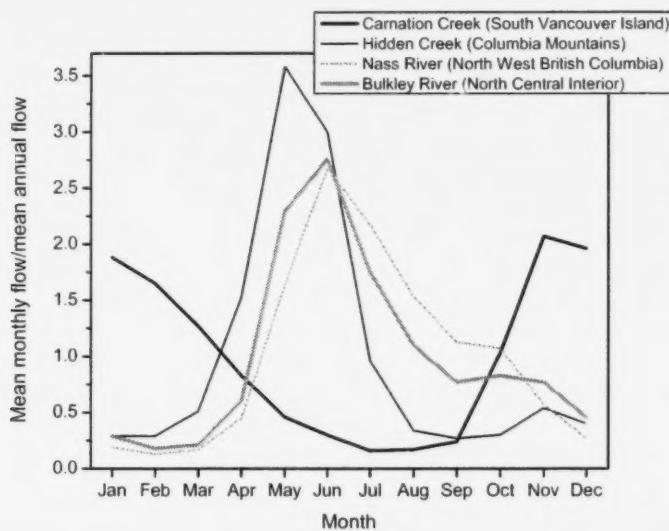


Figure 1. Examples of four hydrological regimes in British Columbia.

During summer, after a prolonged dry period, streamflow is sustained either by snowmelt, glacier melt, the release of stored water, or by any of the above. A secondary low-flow period then typically develops first in basins where snowmelt occurs early in spring or over a short time, i.e., basins at low elevations or with small elevation differences (e.g. Hidden Creek in Figure 1). Otherwise, summer streamflow depends on availability and release of surface storage from lakes and wetlands and subsurface storage from groundwater. Where there is abundant storage, a secondary low-flow period may not develop (e.g. Bulkley River in Figure 1) or may develop during only an exceptional year with low snow pack or with a particularly hot and dry summer. In glaciated basins, increased ice melt contributions during the warm season maintain high streamflow levels beyond the snowmelt period (e.g. Nass River in Figure 1.)

Groundwater flow in alpine areas has only recently emerged as a topic of research, and findings vary with location. Mountain soils and aquifers tend to be shallow with limited storage capacity. During a dry summer, streams from small catchments in the southern part of the Cordillera often go dry in August or September. In a field study at Lake O'Hara in the Rocky Mountains, Hood et al. (2006) found, in contrast, that groundwater contributions to the lake are considerable and remain stable during late summer. Extensive alluvial aquifers in the larger valleys across the region can provide late summer base flow to rivers after being recharged from the river during the spring freshet (Scibec et al. 2007).

In British Columbia, climate influences on low-flow timing and influences of basin-storage properties on streamflow recession and magnitude are modified by elevation and basin hypsography. Low-flow regionalization in mountainous environments is hence challenged by the competing impacts of climate, elevation, geology, and the existence of storage in lakes, wetlands, and glaciers which can vary strongly over short distances. Figure 2 shows the specific discharge of the mean seven-day minimum flow during the summer half-year across British Columbia. Summer low flows vary strongly across the region and low low flow and high low flows may occur in neighbouring basins in the same year while low and high streamflows may occur in neighbouring basins. Generally, however, summer low flow per basin area is lowest in the southern plateau areas and valleys and highest in glaciated high-mountain areas.

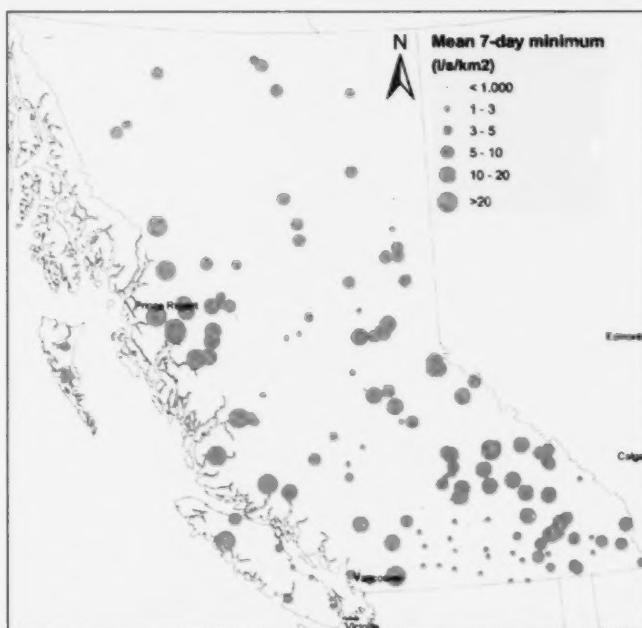


Figure 2. Specific discharge of mean seven-day minimum flow (April 1 to October 31) in British Columbia.

1.2 Environmental change and values threatened by low-flow hazard in British Columbia

Aquatic habitat and life cycles of aquatic species generally adjust to and rely on regular low-flow periods. Similarly, the design of abstraction schemes for public water supply, irrigation, hydropower, etc. is commonly based on a certain recurrence of low flows of particular magnitude. Nevertheless, a lack of water quantity and a deterioration of water quality during extreme low-flow periods may at certain times become a hazard to ecosystems and to water management schemes. Climate change and other environmental changes may increase the occurrence of extreme events and hence decrease the low flows.

While dilution of effluents from industry, mining, etc. can be a problem during both winter and summer low flows in British Columbia, environmental and socio-economic impacts of reduced flows and degraded water quality tend to be greatest during the warm and dry season. Low water levels and high stream temperatures in summer threaten habitat for cold-water species such as salmonids. In dammed rivers, reservoir operation has to be adjusted during low flows to provide

certain in-stream flow targets (mainly for fish but also for other aquatic species). This affects hydropower production during summer. In wetter regions, for example along the coast, municipal water supplies as well as irrigation facilities rely on year-round inflows, even during the summer season. In years with exceptionally dry summers and infrequent low flows, communities may need to impose water restrictions. Due to these impacts, the low-flow hazard model focuses on summer streamflows and how they may be influenced by environmental change.

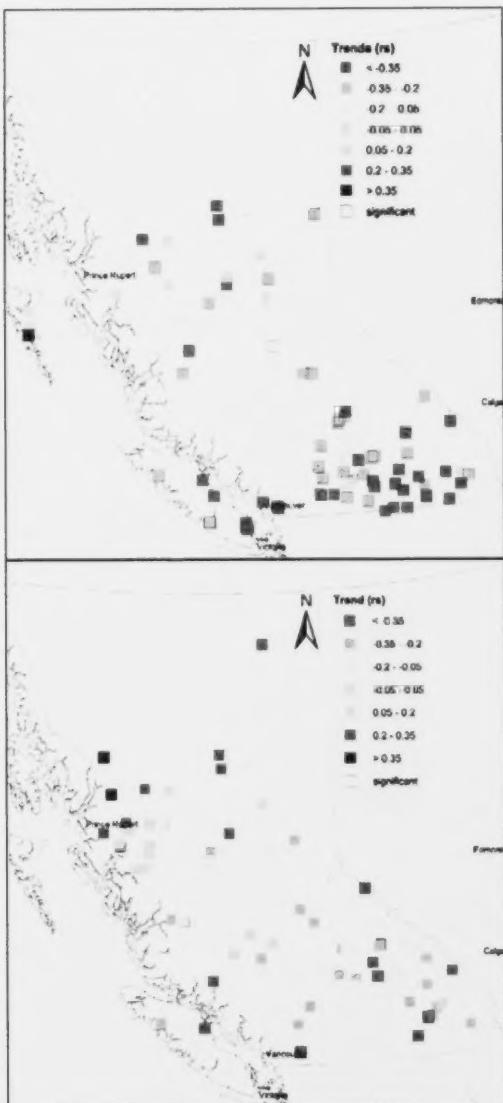


Figure 3. Trends expressed as Spearman rank correlation coefficient (rs) in September streamflow for non-glacierized basins (left) and glacierized basins (right) from 1976–2002 (Moore et al. 2007).

The most extensive land disturbance in British Columbia is forestry (clearcutting and road construction) which now frequently accompanies or follows forest disturbance from the mountain pine beetle (MPB) epidemic. Little research has been done on the impact of deforestation, specifically on low flows. Moore and Wondzell (2005) reviewed the effect of forest harvesting on streamflow. It is commonly assumed that forest harvesting reduces the severity of low flows due to an increase and advance in snowmelt. However, summer low flows may be sensitive to changes in transpiration due to changes in riparian vegetation and other effects such as advanced timing of melt and enhanced melt rates. Therefore, effects from forestry harvesting and disturbance may synchronise with or be in opposition to the effects from climate change and it can be difficult to separate the impact of forest management from that of climate change. The low-flow hazard model focuses on the response of summer low flows to scenarios reflecting forest disturbance and could additionally encompass climate change—see Section 4 for further explanation.

1.3 Low-flow estimation procedures in other jurisdictions

1.3.1 Low-flow standards and their estimation

Many countries have laws and regulations with respect to low flows or require residual flows in their rivers at all times. In general, *design low flows* are needed for abstraction schemes for public water supply and irrigation, for estimating the dilution of industrial and domestic effluents, for estimating the energy that can be generated from hydropower, and for maintaining or improving freshwater ecosystems (for a summary of design low-flow problems, see Gustard et al. 1992). Regulations governing how to determine design low flows vary considerably and depend on what is at risk during the low-flow period.

The most common design low flow is a required residual flow, which is traditionally often defined by a percentile of the flow duration curve or a percentage of the mean flow. In recent years, *in-stream flow* or *environmental flow* requirements and guidelines have been based increasingly on aquatic ecology. After Jowett (1997), *in-stream flow methods* can be divided into three types: historic flow, hydraulic, and habitat methods. A well-known historic flow method is the Tennant (1976) method, which specifies that 10% of the average flow is the lower limit for aquatic life and 30% of the average flow provides a satisfactory stream environment. Later methods such as the range of variability approach (RVA) and the associated indicators of hydrologic alteration (IHA) identify an appropriate range of variation in a set of 32 flow statistics derived from the *natural* flow record (Richter et al. 1997). Hydraulic methods are more site-specific and require measurements of hydraulic data (wetted perimeter, width, depth or velocity) from cross-sections in the stream. The aim of hydraulic methods is to quantify the loss of habitat caused by changes in the natural flow regime. Various habitat models and computer code exist to perform such calculations.

It is not possible to assemble a comprehensive list of design low flows around the world, because some jurisdictions have guidelines or laws that specify how design low flows are to be calculated; others require the use of an in-stream flow method; and yet others specify a specific flow value (Table 1). Switzerland, for example, chose the Q_{347} , the flow that is equalled or exceeded on 347 days per year on average, and hence is the same as the Q_{95} used in Austria. In the USA, this value is called the Q_5 as percentiles of the flow-duration curve are given by their non-exceedance. In Norway, if there are abstractions in a basin, the residual flow must not be less than the *common low flow*. The calculation of this index is complicated: first, the 15 smallest values every year in a daily streamflow record are removed, then annual minimum series are determined from the remaining sample of which, again, one third of the lowest values are removed from the sample. The smallest of the remaining daily annual minimum streamflow is defined as the *common low flow*. Although for Norwegian basins this index is highly correlated with the mean

minimum annual one-day flow and with the Q95 (flow equalled or exceeded 95% of the time), water rights have been based on it for many years and hence it remains to be used.

Table 1. National approaches to low-flow standards and their estimation at ungauged sites (selected examples).

Country	Low-flow statistic	Approach
Switzerland	Q347	one map for entire country (one value)
United Kingdom	flow duration curve	low flows 2000 software (at any point along river)
Austria	Q95	low-flow maps (upper and lower confidence bounds)
Norway	common low flow	regional regression equations to be applied
USA	flow quantile	state by state quantile regressions (StreamStats)
New Zealand	minimum flow	conceptual recession model predicting low flow as the consequence of a season-long period of alternating typical events and recessions (from climate data)

A few small countries have calculated low-flow standards for all watersheds of a certain size or for their entire river networks. The outcomes are published as paper maps (e.g. Switzerland and Austria) or are provided as digital maps or applications where users select a particular point along a river where they would like the low-flow statistic to be estimated (e.g. *Low Flows 2000* in England and Wales, and the *National Water Atlas* of Norway—Table 1). For gauged streams, these would usually be calculated from the observed streamflow record. For ungauged sites the values must be estimated. Estimates of low-flow statistics at ungauged sites can be obtained either by statistical regionalization or by regionalized rainfall-runoff models.

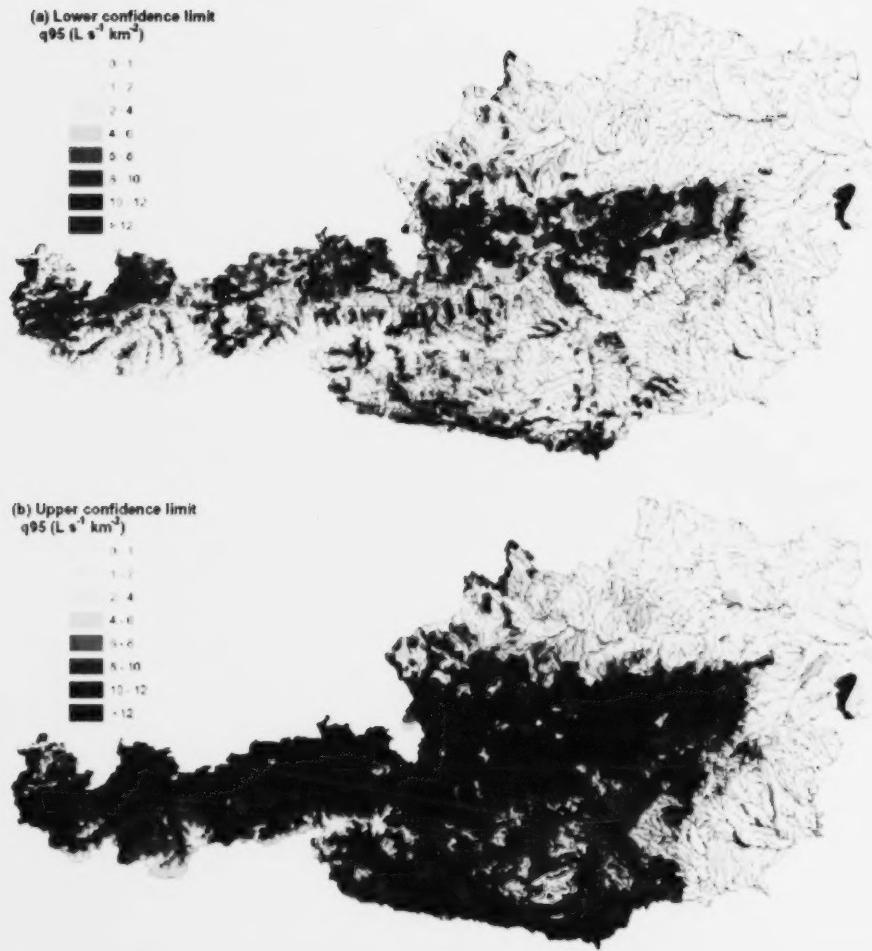


Figure 4. Results of the national low-flow estimation procedure for Austria (from Laaha and Blöschl 2007).

The most common method to estimate design low flows at ungauged sites is to derive the required low-flow statistics from a set of gauged records in the region (usually a geographically and hydrologically homogeneous region) and relate the low-flow statistics to their respective catchment properties by regression analysis, for example. The resulting statistical regionalization model, which may predict the Q95 as a function of catchment properties such as annual precipitation, drainage density, elevation range, soils or geology, can then be applied to predict the low-flow statistic to ungauged streams for which the same catchment information is available. A good example is the recently completed *national low-flow estimation procedure* of Austria (Laaha and Blöschl 2007). It was carried out thoroughly in its consideration of the combination of gauged and ungauged nested catchments and the associated uncertainties. The publication also contains a good review of low-flow estimation procedures in other countries. Figure 4 shows the main result: maps of upper and lower confidence limits of estimates of Q95.

Another approach to determining low-flow characteristics at ungauged sites is the use of a distributed hydrological model applied to an ungauged basin with regionalized climate input and parameters. In Norway, however, a comparison between the performance of a gridded version of the HBV (Hydrologiska Byråns Vattenbalansavdelning) Model was compared to the conventional regional regression estimation to determine a *common low flow* in ungauged catchments

(Engeland et al. 2006). It was found that the conventional regression estimate was superior to the model.

In the UK, the software *Low Flows 2000* is underpinned by regionalized hydrologic models which enable the natural, long-term flow duration curves to be estimated for any UK river reach, mapped at a 1:50 000 scale. Both monthly and long-term annual statistics are provided (Gustard et al. 2004) interactively by clicking on a river reach within a GIS environment. The software also contains information on water licences and abstractions and takes these into account. It can therefore also be used to simulate and test the effect of abstractions along a river.

In other cases, the interest is not in a mean low-flow statistic, but in regional estimates of return periods of certain flow magnitudes at the lower end of the flow-duration curve or in flow durations and deficits below a certain threshold. Here, regional frequency analyses similar to that of floods (e.g. index flood approach or region of influence approach) are commonly used. At-site and regional frequency analysis for low flow and drought is discussed in detail in Tallaksen et al. (2004).

1.3.2 Impact of climate and environmental change on low flow

Few studies worldwide have focused specifically on modeling change in low flow as a response to global climate change. At the continent-to-global scales, scenario modeling experiments have been carried out mostly for many of the major continental river basins and integrate large areas and possibly many different hydrological regimes. Hirabayashi et al. (2008) estimate for the Columbia River that drought days (days with flow below Q90) will increase 3.4-fold by the end of the century. Alcamo et al. (2007) predict no exacerbation of the dry extremes for the North American west despite expected increasing water withdrawals. None of the studies has considered the impact of land-use change. Bloeschl et al. (2007) discuss the lack of research on attribution of land-use versus climate change on high and low flows and, in the case of low flows, identify a scale problem: climate change acts at the large scale, while changes to the basin that influence particular flow characteristics are local. However, there is usually a lack of local information relevant for assessments of change.

In the USA Pacific Northwest, research on changes in hydrologic regimes in recent years has concentrated on the recent shift in snowmelt timing. For western USA, there is considerable evidence that summer low flows have decreased and will further decrease as a result of the extension of the dry period due to earlier snowmelt (Regonda et al. 2005; Stewart et al. 2005). These conclusions result mostly from statistical analyses. As already discussed in Section 1.1, similar findings were made for western Canada (Rood et al. 2008; Whitfield and Cannon 2000); however, systematic trends in summer low flows across British Columbia seem to vary (Moore et al. 2007; Déry et al. 2009).

Only in two articles have authors investigated and showed in more detail the differences in relative importance of groundwater contribution to baseflow and discussed how these differences will affect the vulnerability of low flows to changes in amount and timing of snowmelt (Jefferson et al. 2007; Tague et al. 2008). These show, through two case studies in Oregon, that in a groundwater-dominated watershed, aquifer storage and the associated slow summer recession are responsible for sustaining discharge even when the seasonal or annual water balance is negative, while in a runoff-dominated watershed, subsurface storage is exhausted every summer. On the other hand, base flow fed from deep aquifers may be less vulnerable to climate variability. The authors conclude that groundwater-dominated watersheds may respond more strongly to changes in snowmelt recharge. Such a sensitivity of summer base flow which is sustained from an aquifer that is recharged from snowmelt was also mentioned by Scibek et al. (2007) in a study in Grand Forks, British Columbia (see Section 1.1). Generally, however, it should be noted that there is a great lack in the understanding of competing impacts on low flows, particularly in areas where little is known about the local influences of groundwater.

1.4 Implications for developing a low-flow hazard model for British Columbia

The term *hazard* appears rarely in literature on low flows. Most literature on regionalization of low-flow statistics suggests that low-flow hazard is perceived either in terms of a mean annual n-day low flow (e.g., seven days in the USA) or a percentile of a flow duration curve (e.g., Q95 in Austria). These are generally expressed as m^3/s or, if normalized to the basin area, in mm or $\text{l/s}/\text{km}^2$. There is also a large body of literature that deals with *drought-frequency analysis*. Similar to flood-frequency analysis, drought-frequency analysis aims to calculate return periods for extreme low-flow periods (usually in terms of duration and cumulative—low deficit below a threshold). Most countries with national low-flow estimation strategies are small with well-maintained, dense hydrometric networks that provide a large sample for statistical analysis. The main problem of these statistical methods is that they are estimated from observed data and then regionalized to the ungauged site. These approaches and hence the resulting low-flow standard expressed assume stationarity in climate and land use and a homogeneous streamflow record. In recent times of rapid climate and land-use change, such approaches are questionable (Milly et al. 2008). Although the importance of climate and land-use parameters in the spatial regionalization models suggests a sensitivity of low flow to such changes, the common low-flow estimation procedures cannot assess potential impacts of climate and environmental change on the probability of a certain low-flow statistic to change.

In fact, changes to low flows have rarely been investigated. Generally, this task requires a hydrological model that can be driven with scenario input and can model *outside* the envelope of past conditions. In general, most modeling studies on hydrological change deal with the response of annual yield or the entire hydrograph to future scenarios. In most cases, the hydrologic models used for the assessment poorly fit the low-flow period of the hydrograph and can therefore not reliably predict future low flows. There are two main reasons for this caveat. First, hydrological models are rainfall-runoff models, meaning they are designed to model runoff events most accurately, not *no-runoff periods*. In addition, objective functions such as the Nash–Sutcliffe efficiency (Nash and Sutcliffe 1970) used in the calibration process emphasize a good fit to high flows and tend to overestimate goodness of fit in strongly seasonal regimes (Schäefli and Gupta 2007). Second, the relevant storage-release behaviour of the catchment as well as human impacts such as abstractions vary locally over short distances. Data on abstractions, groundwater levels, and aquifer productivity are needed to validate assumptions on groundwater contribution to base flow, but may be unavailable. In British Columbia, outside the most populated southwest and some cultivated valleys in the Okanagan, groundwater observation wells are lacking and, where they do exist, they tend to be influenced by nearby abstraction wells (Moore et al. 2007).

As there is no common or accepted method or model to assess the impact of environmental change on low flows and as there has been particularly little work on the sensitivity of low flows to forest change, a new approach had to be developed. The approach makes use of combining the following:

- the extensive knowledge and experience in the literature on regionalization of low flow, specifically on catchment characteristics that influence the low-flow-relevant characteristics of the hydrograph such as the recession period; and
- a specific adaptation of an accepted continuous water balance model with the model fit and performance optimised for the summer low-flow period.

A hazard model, however, needs to be more flexible than classic low-flow regionalizations in that it shouldn't assume stationarity. A major challenge will be to capture the correct storage-release

behaviour at the local scale of interest while accounting for potentially strong differences of this behaviour across British Columbia.

Our aim in this study is to develop a tool to predict the impact of environmental change, particularly the mountain pine beetle epidemic, on low flows for a large region within British Columbia. Specific objectives for the model include:

- to correctly predict the magnitude and duration of the typical summer low-flow period in different hydrological regimes based on climate input and watershed information;
- to incorporate in the low-flow model explicit consideration of the hydroclimatic processes governing the low-flow response of the watershed to changed forest conditions;
- to include in the model sufficient parameters to enable regionalization of the model for application to ungauged watersheds; and
- to ultimately map potential low-flow changes and their uncertainty as a response to forest change scenarios over a large region.

We describe here the development of the model structure and the first tests of model performance for watersheds gauged by the Water Survey of Canada. In addition, the Ministry of Environment's low-flow data sets (spot gauging of British Columbia rivers during selected droughty years) have been evaluated for use in model development, but the measurements have been too irregular to support model calibration at this stage. When the regionalization of the envisioned revised model is complete (see Section 4.2) and can model the summer low flow for all third-order watersheds across the Fraser basin, the Ministry of Environment data sets would potentially provide useful measures of validation.

2 Description of the low-flow model

2.1 Structure

The general approach of the low-flow model is to transform a typical temporal water input (or lack of input) into a temporal watershed output (hydrograph). This can generally be achieved with a storage-outflow relationship. The outflow, or discharge, is functionally related to the catchment's water storage. The storage-outflow function constitutes the core of the model. Simple storage models used most commonly in hydrological models assume a function that describes a linear relationship between storage and discharge, which results in an exponential hydrograph recession during periods of no input. More complex—and ultimately more flexible—functions can be built. Ideally, the parameters of such a function (model) will link a typical streamflow recession behaviour to certain basin characteristics. This means that while the general function is considered the same everywhere, its parameters depend on basin characteristics that can be derived from maps. This relation, which must first be determined using a set of gauged test watersheds (a process called *regionalization*) then gives the values of the function's parameters for ungauged watersheds (see Section 1).

Applying such a storage-discharge model to each third-order watershed will generate unique output for each watershed because:

1. Climate inputs will differ depending on elevation, location, land-use, etc.; and
2. The parameter values of the model (describing the storage-outflow relationship) will differ in relation to basin characteristics.

Figure 5 gives a visual overview of the model components and their interactions at different spatial resolutions.

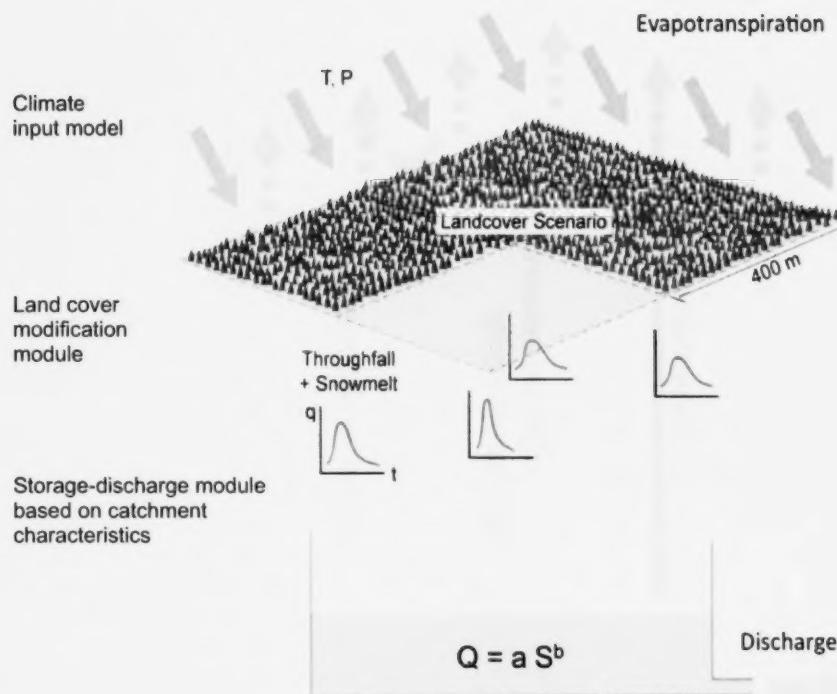


Figure 5. Schematic of the low-flow model (description in text).

The model consists of a climate input module, a land cover modification module and a storage-discharge module. The climate input module and the land cover modification module are similar to the modules for the peak-flow model and are described there (Carver et al. 2009). This means that they are based on climate normals and the low-flow model, similar to the peak-flow model can hence be considered a *regime* model at this point. The output of the land cover modification module, which is a combination of snowmelt and throughfall, is then transformed into discharge in the stream for each third order watershed based on a specific storage-discharge relationship in the storage-discharge model. With this model and additional information from streamflow records and physiographic information from the third-order watersheds in the Fraser River basin, the following components are developed or used:

Input

Spatially distributed output (400-m grid cell) from the climate normals input and land cover modification modules are calculated for a selected watershed for selected gauged watersheds using the method and parameterization from the peak flow model (Figure 5).

Input modification

Potential evapotranspiration (PET) and actual evapotranspiration (AET) for the selected watershed are determined from radiation and temperature normals data and the proportion between AET and PET is predicted based on land cover, also using method and parameterization from the peak flow model. Losses due to AET are directly removed from the storage.

Calibration

The general storage-discharge relationship function is defined as: $Q = a S^b$. The two parameters a and b of this storage-discharge module are then calibrated using a Generalized Likelihood Uncertainty Estimation (GLUE) framework with a Monte Carlo procedure, which samples a large number of possible parameter sets. The details of implementing this procedure, which has

become a standard in hydrological model calibration in recent years, is explained in Wagener and Kollat (2007). It also allows the specification of the uncertainty of the predicted hydrograph by giving confidence limits for each time step.

Regionalization of model parameters

Steps 1–3 are performed for a large set of watersheds. For this set, extracted watershed characteristics are presumed to be related to the model parameters. Such characteristics include geology and soils, physiographic properties, etc. Then, the optimized parameters from the set of test watersheds are related to these catchment characteristics by multiple linear regression, i.e., a statistical model is found to predict a and b with basin characteristics. Once a regression model is found that allows the parameters to be predicted with enough confidence, parameters a and b can be calculated for any watershed within the Fraser basin that falls within the same area range as the set of watersheds selected to perform the regression.

Application of scenarios

Scenarios based on different combinations of beetle infestation and the degree of salvage harvest (see scenario details in Carver et al. 2009) are calculated for:

- the selected gauged watersheds, and
- ungauged watersheds (given the regionalization was performed successfully and the parameters are estimated with reasonable certainty).

The calibration procedure of step 3 is visualized here for a sample watershed (Lingfield Creek near the Mouth 08KE024). The output from the climate input and land cover modification modules is used and the parameters are optimized (Figure 6). The surface of the Nash–Sutcliffe objective function (see Section 4.3.1) is presented on the left side with an optimum at $a=16.45$ and $b=0.48$ for the two parameters. If $b=1$, the storage-discharge relationship is linear. As can be seen on the right side of Figure 6, the simulated hydrograph based on the climate input fits well the mean observed daily discharge with an efficiency of 0.98 for the logarithmic discharge values. Also, the water balance is simulated well with a total runoff of 638 mm vs. 617 mm.

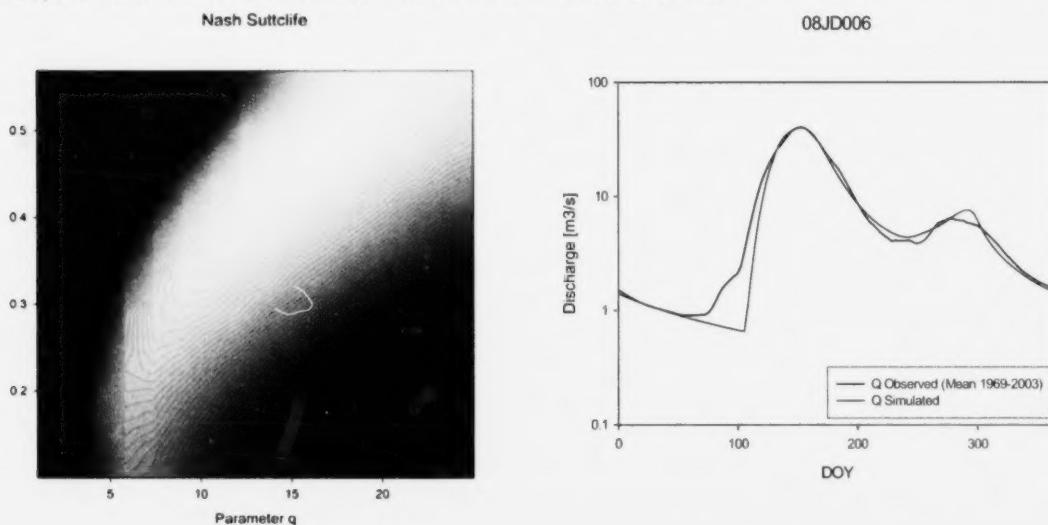


Figure 6. Parameter optimization (a,b) for the storage-discharge relationship and discharge results for the Lingfield Creek watershed (08KE024).

2.2 Data Inputs

Table 2 provides an overview of the key data inputs.

Table 2. Overview of input data.

Input Data	Data Name	Data Provider	Spatial Resolution	Data Citation	Used in...
Precipitation	ClimateBC	Centre for Forest Gene Resource Conservation, UBC; Research Branch, BCMoFR	400 m	Spittlehouse (2006)	Climate Input Module
Temperature	ClimateBC	Centre for Forest Gene Resource Conservation, UBC; Research Branch, BCMoFR	400 m	Spittlehouse (2006)	Climate Input Module
Streamflow		Environment Canada; Water Survey of Canada	-		Calibration of Storage-Discharge Module
Topography	PRISM Digital Elevation Model	BC MoE; UBC	25 m		Parameter Regionalization
Vegetation	BTM1	BCMoE, Surveys and Resource Mapping Branch	1:250 000	BCMoE (1995)	Land Cover Modification Module
	Pine Cover		400 m	Eng et al. (2006)	Land Cover Modification
Hydrology	Watershed Atlas	BC MoE, Fisheries Branch	1:50000	BCMoE, Fisheries Branch (1996)	Parameter Regionalization
Disturbance	MPB	Forest Health Factor Data Research Branch, British Columbia Forest Service	Polygon	Eng et al. (2006)	Land Cover Modification
Geology		BC Ministry of Energy, Mines and Petroleum Resources	Polygon	http://www.em.gov.bc.ca/Mining/Geolsurv/Publications/catalog/bcgeolmap.htm	Runoff Module Parameter Regionalization

3 Model Application

3.1 Study Area

The Fraser basin covers 231500 km², which is 24.5% of the land of British Columbia (BCMoE 1995). The model is applied to a collection of third-order watersheds within the Fraser basin. This first model test presented here concentrates on basins that receive little influence from lakes and glaciers. Base flow is strongly influenced by storage in the watershed. Surface water reservoirs such as lakes and glaciers take a special role as they continuously feed river flow during dry periods when low flows would otherwise occur. Hence, watersheds with a considerable area covered by lakes, wetlands, or glaciers can be considered insensitive to forest-driven changes in low flow. Furthermore, only the smallest catchments were selected. The larger the watershed, the greater the number of competing influences that act on the hydrograph. Considering the main goal—namely, to isolate cause and effect of specific catchment characteristics for future regionalization—we sampled watersheds with similar surface areas as the relatively small third-order watersheds which the regionalized model will ultimately simulate. However, given the paucity of small watersheds with gauging data, some samples are composed of multiple third-order watersheds.

Few watersheds within the Fraser basin (Figure 7) have sufficiently long streamflow records. Table 3 gives an overview of the watersheds and gauging records used, along with some of their basic catchment characteristics. Watersheds range from 47 km² to 575 km² in area and from 182 mm to 1820 mm in annual runoff.

Table 3. Watersheds for testing of the low-flow model.

ID	Name	Years of record	Area	Elevation	Annual runoff (mm)	Regime
08JA014	VAN TINE CREEK	29	153	1394	185	Snow-rain
08JD006	DRIFTWOOD RIVER	22	407	1295	597	Snow-rain
08JE004	TSILCOH RIVER	28	414	1003	182	Snow-rain
08KB006	MULLER CREEK	36	134	1507	1100	Snow-rain
08KE024	LITTLE SWIFT RIVER	30	133	1583	652	Snow-rain
08KH019	MOFFAT CREEK	29	539	1348	200	Snow-rain
08LB024	FISHTRAP CREEK	21	135	1338	185	Snow-rain
08LB076	HARPER CREEK	40	168	1749	748	Snow-rain
08MA006	LINGFIELD CREEK	40	98.4	1888	244	Snow-rain
08ME025	YALAKOM RIVER	37	575	1922	238	Snow-rain
08MH076	KANAKA CREEK	45	47.7	460	1820	Rain

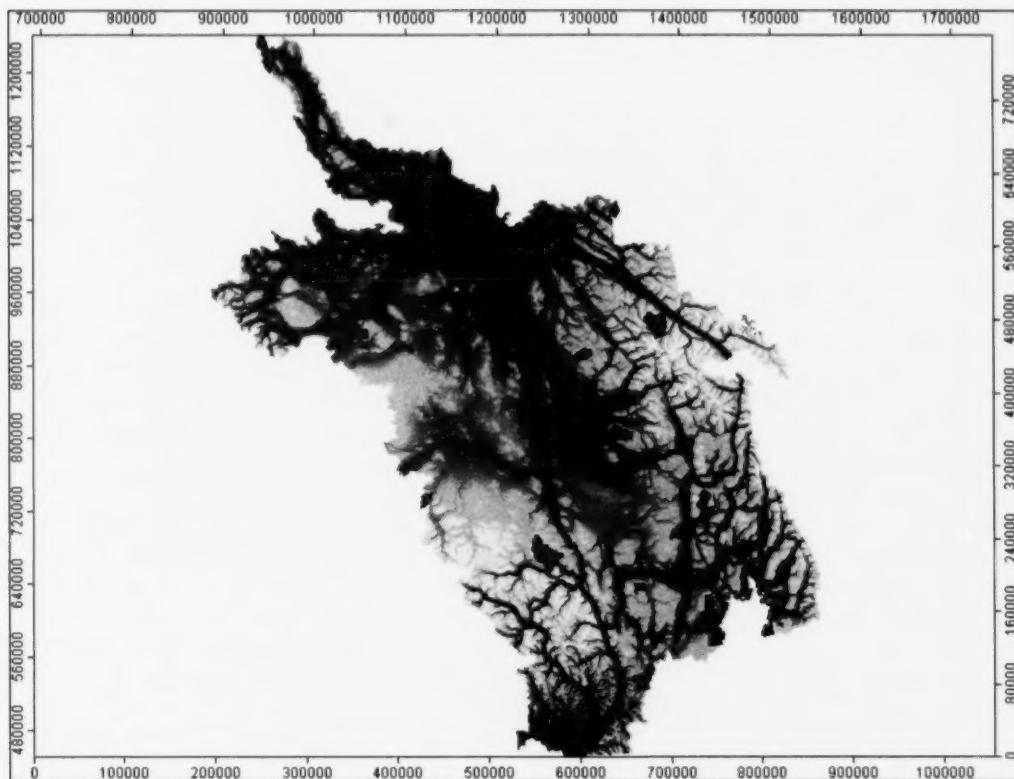


Figure 7. Location of the selected test watersheds in the Fraser River basin.

3.2 Scenarios

Medical issues prevented the team from completing detailed scenario development—including developing the climate input and land-cover modification modules required for scenario analysis—by the NRCan deadline.

The model is designed to use the throughfall and snowmelt from the peak-flow model's climate input module. Therefore, the regionalized model will ultimately implement the same scenarios applied for the peak-flow study. As this calculated scenario input was unavailable prior to the Natural Resources Canada submission deadline, results are instead presented from an alternative test, applied while developing the model, based on a previous (different) climate input (Schneider 2008). The example serves equally well to demonstrate the model's performance. Future scenarios applied at this point in model development reflect only the change in low-flow hazard due to a change in interception, rainfall and snow dynamics (resulting from pine death and salvage harvest or climate change). The additional (potential) direct impact on summer streamflow from modified evapotranspiration is yet to be fully incorporated into the model.

Two scenarios are applied to the test watersheds:

1. Past conditions. These conditions are based on 1995 Baseline Thematic Mapping (land cover) and 1961–90 climate normals from the ClimateBC dataset (Spittelhouse et al. 2006). They are used for model calibration, and the results provided in the following section are referred to as simulated.

2. International Panel on Climate Change (IPCC) Climate Scenario SRES B1. These conditions are based on temperature and precipitation change factors simulated by the Canadian Global Climate model CGCM2 available in the ClimateBC application (Spittlehouse 2007). The B1 Scenario prescribes a further increase in greenhouse gases until the middle of the 21st Century.

3.3 Results

3.3.1 Model calibration

Model fit was assessed using two common objective functions (performance criteria): the Nash–Sutcliffe Model Efficiency (NSeff) and the Root Mean Squared Error (RMSE). Both were calculated for a large set of potential parameters in a Monte Carlo procedure. The criteria were calculated for the entire year and for the part of the year with flow below Q50 (NSeff low flow). NSeff ranges from 1 to $(-\infty)$, with one denoting a perfect fit and zero meaning that the model is no better than using the mean as the model prediction. A low RMSE denotes a good fit.

Table 4 shows the fitted parameters a and b and the measures of goodness of fit. Generally, good model fits are obtained. However, closing the water balance sometimes required correcting the input (rain and snow) to the watersheds.

Table 4. Model parameters and goodness of fit for the test watersheds.

ID	Parameter a	Parameter b	Input correction	NSeff	Log NSeff	NSeff (Low Flow)	RMSE	RMSE (Low Flow)
08JA014	55.99	0.11	1.1	0.80	0.74	0.74	0.53	0.32
08JD006	29.02	0.48	1	0.94	0.83	0.98	4.37	0.96
08JE004	92.03	0.08	1	0.72	0.87	0.77	1.41	0.77
08KB006	35.34	0.60	1.4	0.94	0.94	0.96	1.13	0.62
08KE024	39.08	0.13	1.7	0.19	0.72	0.67	1.68	1.12
08KH019	77.16	0.08	1	0.76	0.93	0.87	1.02	0.76
08LB024	27.41	0.40	1.15	0.94	0.85	0.99	0.41	0.06
08LB076	83.22	0.24	1.6	0.87	0.76	0.93	2.40	0.76
08MA006	59.54	0.07	1.2	0.80	0.84	0.80	0.46	0.28
08ME025	87.59	0.31	1	0.98	0.98	0.99	0.50	0.19
08MH076	23.00	0.90	1.3	0.90	0.86	0.94	0.62	0.38

Figures 8 and 9 show two examples of fitted hydrographs, one with a low efficiency (Tsilcoh River) and one with a high efficiency (Muller Creek). Tsilcoh River is the driest watershed in the sample of test basins and has a very low summer flow with a recession that seems to have multiple phases. The watershed has a short and early snowmelt, but the model simulates a snowmelt peak that is too narrow. As a result, the recession is not fitted correctly and summer low flow is overestimated.

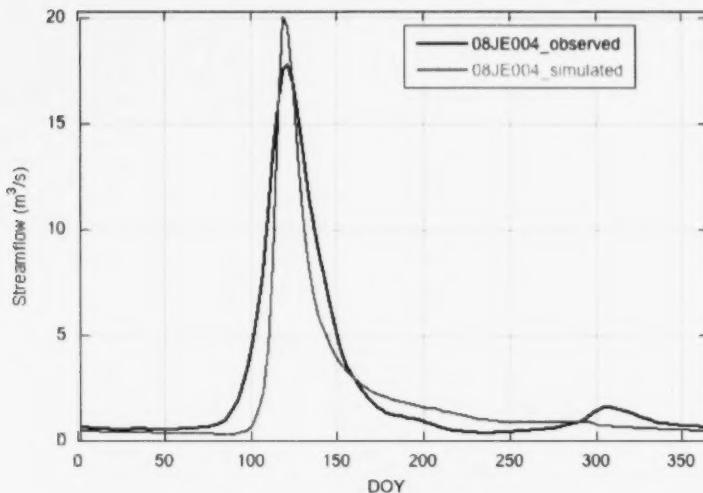


Figure 8. Model fit for 2007 conditions for Tsilcoh River, 08JE004.

Muller Creek (Figure 9) illustrates the problem that many British Columbian rivers don't have a true summer low flow. In this high-elevation watershed, snowmelt lasts well into the summer, and the recession flattens and creates a secondary minimum only just before the autumn rain begins. While the magnitude of the short summer low flow is well-simulated, the duration is not, because the climate input data does not capture the variability of the autumn rain. Winter low flow is still much lower than the secondary minimum in the autumn.

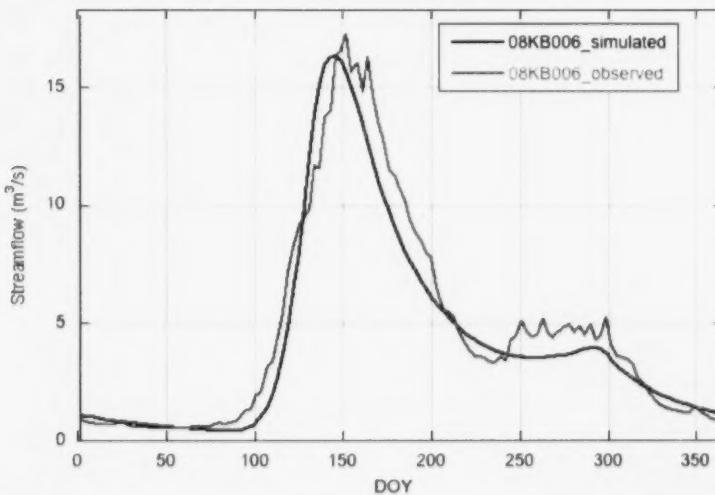


Figure 9. Model fit for 2007 conditions for Muller Creek, 08KB006.

3.3.2 Scenarios

Recent and simulated discharges and uncertainty domains are tested using the Kolmogorov-Smirnov significance test to illustrate the change from baseline under the climate change scenario. Its null hypothesis ($h=0$) is that the variables X_1 and X_2 are drawn from the same continuous distribution. The alternative hypothesis ($h=1$) is that they are drawn from different distributions and indicate a failure to reject the null hypothesis at the 5% significance level. In this case, X_1 and X_2 are the values at a particular day of the year simulated by the model with the 1000 parameter sets used within the Monte Carlo simulation that ran using the calibration procedure of the parameters a and b of the model.

The example for the Little Swift River in Figure 10 shows significant changes during peak flow due to snow melting earlier, which causes significant changes during the recession. The lowest summer flows are lower in the climate change scenario, but considering model uncertainty, cannot be considered statistically significant. In summary, while the shift in timing is significant, the resulting change in summer low flow cannot be considered significant.

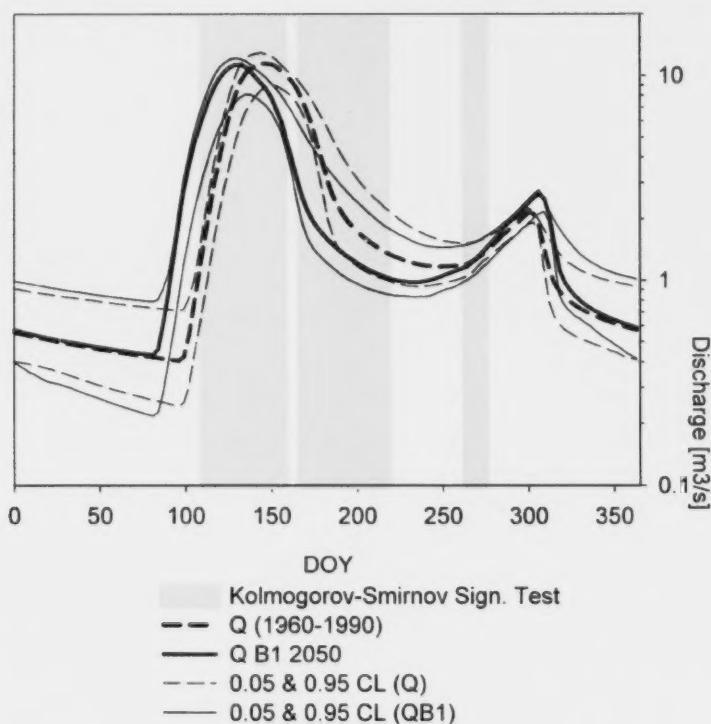


Figure 10. Streamflow changes simulated for the Little Swift River as a response to the SRES B1 climate change scenario (grey areas denote significant change).

3.3.3 Regionalization potential

Relations between the model parameters a and b and selected catchment characteristics are tested to evaluate the potential for model parameter regionalization. Table 5 shows some of these characteristics for the test watersheds. Table 6 shows the Pearson correlation coefficients with the parameters. Most correlation coefficients are low, but the correlations—e.g., with elevation and some geological characteristics—suggest that they may, in combination with other topographic indices, be suitable predictors of the model parameters.

Table 5. Selected catchment characteristics for all test watersheds.

Parameters		Area (km ²)	Elevation (masl)	Geology					
a	b			% Quater- nary	% volcanic	% sedimen- tary	% intrus- ive	% meta- morphic	% Lime- stone
55.99	0.11	153	1394	70.53	73.8	0.03	25.32	0.59	0.26
29.02	0.48	407	1295	44.27	56.7	41.89	1.4	0	0
92.03	0.08	414	1003	80.63	42.05	57.95	0	0	0
35.34	0.60	134	1507	20.09	0	53.16	0	0	46.85
39.08	0.13	133	1583	0.00	0	0	0	100	0
77.16	0.08	539	1348	41.21	61.68	26.27	12.06	0	0
27.41	0.40	135	1338	0.00	8.2	73.39	18.41	0	0
83.22	0.24	168	1749	0.00	2.64	0.01	0	97.35	0
59.54	0.07	98.4	1888	17.43	3.26	94.77	0	1.97	0
87.59	0.31	575	1922	11.06	39.01	52.8	3.1	5.08	0
23.00	0.90	47.7	460	54.21	4.53	17.6	0	77.87	0
Corr. coeff. with a	0.60	0.39	0.13	0.32	0.00	-0.07	-0.11	-0.25	
Corr. coeff. with b	-0.31	-0.56	0.00	-0.34	-0.03	-0.25	0.18	0.36	

Rows correspond to individual test watersheds.

Table 6. Pearson correlation coefficients of selected catchment characteristics with calibrated model parameters a and b (lower part).

Characteristic	Watershed		Correlation with Parameter	
			a	b
Area		0.6		-0.31
Elevation		0.39		-0.56
%Quaternary		0.13		0
%Volcanic		0.32		-0.34
%Sedimentary		0		-0.03
%Intrusive		-0.07		-0.25
%Metamorphic		-0.11		0.18
%Limestone		-0.25		0.36

4 Discussion

4.1 Model performance and validation

An independent validation of the model was not possible at this stage because model parameters have not been regionalized. Still, the test watersheds's results evaluation shows that the model overestimates summer low flow for most of the chosen examples, often because it doesn't capture the steepness of the recession. Therefore, the model must be refined before transferring results to ungauged watersheds.

4.2 Data issues and knowledge gaps

The two most important factors influencing summer streamflow that still need to be adequately modelled are:

1. The poor availability of spatially detailed hydrogeologic information; and
2. A knowledge deficit on the impact of forest change on vegetation period evapotranspiration (and ultimately on the water balance).

Most countries with a history in low-flow and base-flow research have invested heavily in mapping aquifers and hydrogeologic classification. The prime example is the derivation of the HOST (Hydrology of Soil Types) classes (soil types classified by their hydrologic characteristics) regionalization in the UK. Such work has never been attempted in British Columbia, where groundwater is largely used only locally. The lack of a detailed hydrogeology for British Columbia makes any estimation of groundwater-fed baseflow a challenging task. In addition, the geological information from which such properties could be derived is available at only very coarse scales.

Research on the impact of forest change on streamflow has focused mainly on yield and peak-flow response. The impact on low flows during the vegetation period has not been studied. The only study the authors found was done in the former USSR and is not easily accessed nor is it documented well in English.

4.3 Methodological limitations

The sensitivity of the model parameters to catchment characteristics was not obvious in this first application. This may be due to a real insensitivity of the model parameters, inadequacy of the catchment characteristics, or the small sample size of watersheds modeled. The temporal resolution of the climate and streamflow data is likely a significant factor. Year-to-year variability of the summer season recession may be too great, resulting in too much smoothing of the streamflow signal. A study in New Zealand used typical weather sequences instead of averages for low-flow regionalization (see Section 1). Many regionalization studies use a *Master Recession Curve* which may preserve the typical outflow behaviour better than by averaging. It may be useful to compare such approaches with the current approach of disaggregating normals.

4.4 Model flexibility

The model is currently designed for non-glacierized watersheds and watersheds with a low influence of lakes. This limits the possibility of aggregating a low-flow sensitivity to larger watersheds. The possibility to account for the low-flow augmentation from tributaries with high glacier or lake influence would have to be investigated. Stahl and Moore (2006) estimated that for a glacier percentage greater than 5%, low flow is augmented considerably during hot and dry summer periods. A similar study for lake percentage may be useful.

4.5 Next steps

As climate data are now becoming available from interpolation and high resolution reanalysis, it appears useful to use long time-series of daily values to derive the model parameters. The model then needs to be calibrated to a larger sample of watersheds to obtain enough parameter estimates for statistical regionalization. Therefore, the area criteria must be relaxed and larger watersheds must be included. Consequently, it may then be useful to also plan the application to ungauged watersheds for a scale larger than third-order watersheds.

For the regionalization, it may be useful to obtain from the literature some knowledge on hydrogeologic properties (such as hydraulic conductivity) related to certain rock types, or to find other proxies for aquifer productivity.

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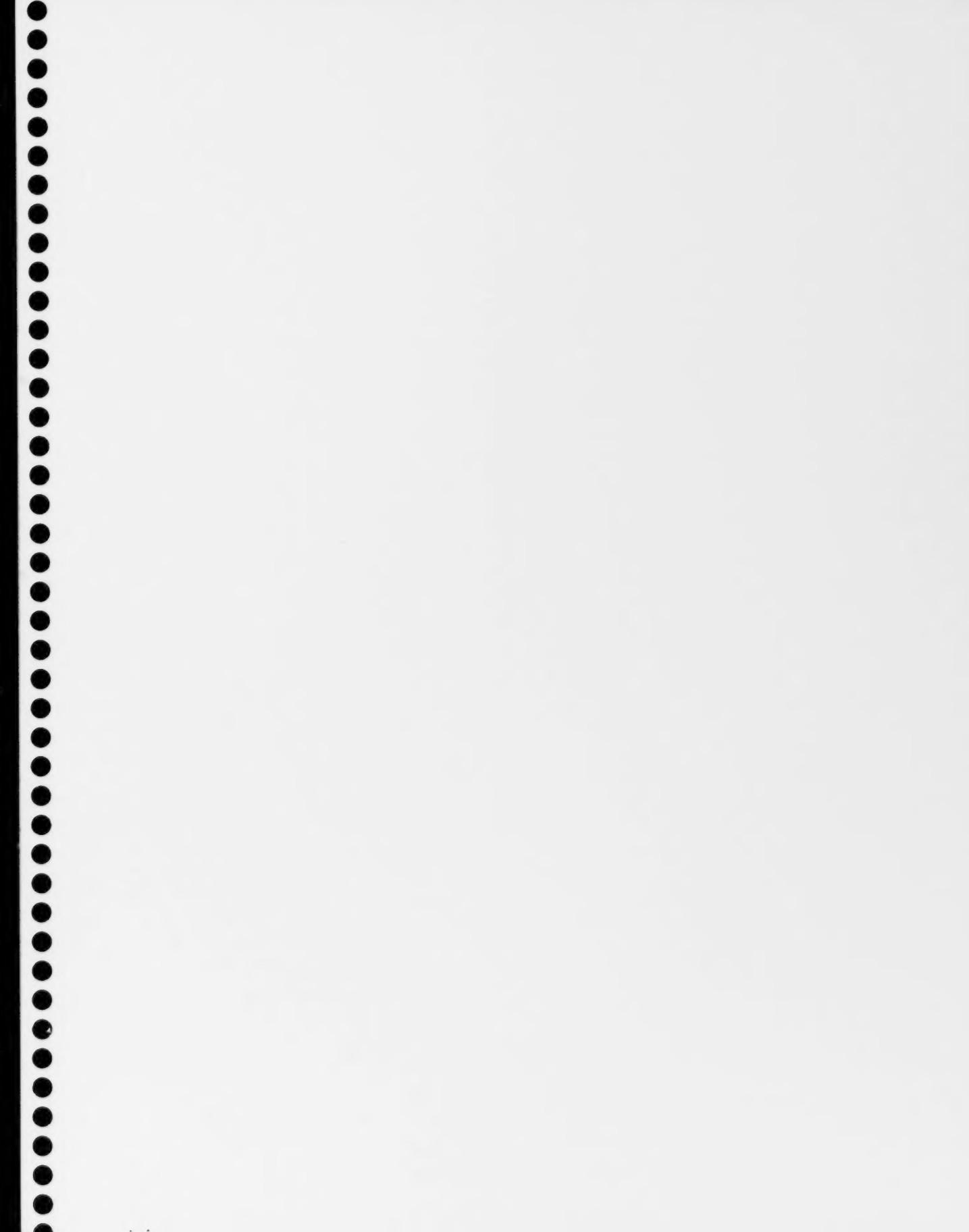
7 Literature Cited

- Alcamo, J.; Flörke, M.; Märker, M. 2007. Future long-term changes in global water resources driven by socio-economic and climatic change. *Hydrological Sciences Journal* 52:247–275.
- Blöschl, G.; Ardoine-Bardin, S.; Bonell, M.; Dorninger, M.; Goodrich, M.; Gutknecht, D., Matamoros, D.; Merz, B.; Shand, P.; Szolgay, J. 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes* 21:1241–1247. doi: 10.1002/hyp.6669.
- (BCMoE) Ministry of Environment, Lands and Parks, Surveys and Resource Mapping Branch. 1995. Baseline thematic mapping: Present land use mapping at 1:250 000, Release 1.0, British Columbia specifications and guidelines for geomatics, Content Series Volume 6, part 1.
- Burn, D.; Buttle, J.; McCollough, G.; Spence, C.; Stahl, K. 2008. The processes, patterns and impacts of low flows across Canada. *Canadian Water Resources Journal* 33:107–122.
- Burn, D.H.; Hag Elnur, M.A. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology* 255:107–122.
- Carver, M.; Weiler, M.; Stahl, K.; Scheffler, C.; Schneider, J.; Naranjo, J.A.B. 2009. Development and application of a peak flow hazard model for the Fraser basin (British Columbia). Report to Natural Resources Canada (Canadian Forest Service), Victoria, BC, Project #7.29. 37 p.
- Déry, S.J.; Stahl, K.; Moore, R.D.; Whitfield, P.H.; Menounos, B.; Burfords, J.E. 2009. Detection of runoff timing changes in pluvial, nival and glacial rivers of Western Canada. *Water Resources Research* 45, 11 p. W04426, doi:10.1029/2008WR006975.
- Eng, M.; Fall, A.; Hughes, J.; Shore, T.; Riel, B.; Walton, A.; Hall, P. 2006. Provincial-level projection of the current mountain pine beetle outbreak: Update of the infestation projection based on the 2005 provincial aerial overview of forest health and revisions to "the model" (BCMPB.v3). British Columbia Ministry of Forests (Research Branch), Victoria, BC. 7 p.
- Engeland, K.; Hisdal, H.; Beldring, S. 2006. Predicting low flows in ungauged catchments. In S. Demuth, E. Planos, F. Scatena, E. Servat, eds. *Climate variability and change: Hydrological impacts*. IAHS Publ. no. 308:158–168.
- Gustard, A.; Bullock, A.; Dixon, J.M. 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report no. 108, Wallingford, UK.
- Gustard, A.; Young, A.R.; Rees, G.; Holmes, M.G.R. 2004. Operational hydrology. Pages 455–484 in L.M. Tallaksen and H.A.J. van Lanen, eds. *Hydrological drought: Processes and estimation methods for streamflow and groundwater*. Development in Water Sciences no. 48. Elsevier, The Netherlands.
- Hirabayashi Y.; Kanae S.; Emori S.; Oki T.; Kimoto M. 2008. Global projections of changing risks of floods and droughts in a changing climate. *Hydrological Sciences Journal* 53(4):754–772.
- Hood, J.L.; Roy, J.W.; Hayashi, M. 2006. Importance of groundwater in the water balance of an alpine headwater lake. *Geophysical Research Letters* 33, L13405, doi:10.1029/2006GL026611.
- Jefferson, A.; Nolin, A.; Lewis, S.; Tague, C. 2007. Hydrogeologic controls on streamflow sensitivity to climate variation. *Hydrological Processes* 22(22): 4371–4385.

- Jowett, I.G. 1997. Instream flow methods: A comparison of approaches. *Regulated Rivers: Research and Management* 13(2):115–127.
- Laaha, G.; Blöschl, G. 2007. A national low flow estimation procedure for Austria. *Hydrological Sciences Journal* 52(4):625–644.
- Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. 2008. Stationarity is dead: Whither water management? *Science* 319:573–574.
- Moore, R.D. 2006. Stream temperature patterns in British Columbia, Canada, based on routine spot measurements. *Canadian Water Resources Journal* 31:41–56.
- Moore, R.D., Allan, D.A., Stahl, K. 2007. Climate change and low flows: Influences of glaciers and groundwater. Final report to the Government of Canada's Climate Change Impacts and Adaptation Program (Climate Action Fund). Natural Resources Canada. UBC, Vancouver, BC. 114 p.
- Moore, R.D.; Scott, D.F. 2005. Camp Creek revisited: Streamflow changes following salvage harvesting in a medium-sized, snowmelt-dominated catchment. *Canadian Water Resources Journal* 30:331–344.
- Moore R.D.; Wondzell, S.M. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: A review. *Journal of the American Water Resources Association (JAWRA)* 41(4):753–784.
- Nash, J.E.; Sutcliffe, J.V. 1970. River flow forecasting through conceptual models part I: A discussion of principles. *Journal of Hydrology* 10:282–290.
- Regonda, S.K.; Rajagopalan, B.; Clark, M.; Pitlick, J. 2005. Seasonal cycle shifts in hydroclimatology over the Western United States. *Journal of Climate* 18:372–384.
- Richter, B.D.; Baumgartner, J.V.; Wigington, R.; Braun, D.P. 1997. How much water does a river need? *Freshwater Biology* 37:231–249.
- Rood, S.B.; Pan, J.; Gill, K.M.; Franks, C.G.; Samuelson, G.M.; Shepherd, A. 2008. Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology* 349:397–410.
- Schaefli, B.; Gupta, H.V. 2007. Do Nash values have value? *Hydrological Processes* 21(15):2075–2080.
- Schneider, J. 2008. Impacts of climate change on catchment storage, stream flow recession and summer low flow. Diploma thesis. Institut für Hydrologie, Freiburg. (Pdf available on request).
- Scibek, J.; Allen, D.M.; Cannon, A.J.; Whitfield, P.H. 2007. Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. *Journal of Hydrology* 333:165–181.
- Smakhtin, V.U. 2001. Low flow hydrology: A review. *Journal of Hydrology* 240:147–186.
- Spittlehouse, D.L. 2007. Climate change, impacts and adaption scenarios. In Ministry of Forests and Range (ed. Technical Report 045. <http://www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr045.pdf> Accessed 24.11.2008.
- Spittlehouse, D. L. 2006. ClimateBC: Your access to interpolated climate data for BC. *Streamline Watershed Management Bulletin* 9:16–21.

- Stahl K.; Moore, R.D. 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. *Water Resources Research* 42. W06201, doi:10.1029/2006WR005022.
- Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across Western North America. *Journal of Climate* 18:1136–1155.
- Tague, C.; Farrell, M.; Grant, G.; Choate, J.; Jefferson, A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change* 86:189–210. DOI 10.1007/s10584-007-9294-8.
- Tallaksen, L.M.; Madsen, H.; Hisdal, H. 2004. Frequency analysis. Pages 199–271 in L.M. Tallaksen and H.A.J. van Lanen, eds. *Hydrological drought: Processes and estimation methods for streamflow and groundwater*. *Development in Water Sciences* no. 48. Elsevier, The Netherlands.
- Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation, and related environmental resources. Pages 359–373 in J.F. Orsborn and C.H. Allman, eds. *Proceedings of the symposium and speciality conference on instream flow needs II*. American Fisheries Society, Bethesda, MD.
- Wagener, T. and Kollat, J. 2007. Visual and numerical evaluation of hydrologic and environmental models using the Monte Carlo Analysis Toolbox (MCAT). *Environmental Modeling and Software* 22:1021–1033.
- Whitfield, P.H. 2008. Improving the prediction of low flows in ungauged basins in Canada in the future. *Canadian Water Resources Journal* 33:207–214.
- Whitfield, P.H. 2001. Linked hydrologic and climate variations in British Columbia and Yukon. *Environmental Monitoring and Assessment* 67:217–238.
- Whitfield, P.H.; Cannon, A.J. 2000. Recent variations in climate and hydrology in Canada. *Canadian Water Resources Journal* 25:19–65.
- Whitfield, P.H.; Wang, J.Y.; Cannon, A.J. 2003. Modelling future streamflow extremes: Floods and low flows in Georgia basin, British Columbia. *Canadian Water Resources Journal* 28(4):633–656.





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